6. The wet switching surge strength of station post insulators in the 1,300 to 2,100 BIL range, both positive and negative, has been found to slightly exceed that of the wet 60-cycle peak.

7. The negative dry switching surge strength of station post insulators can be greatly reduced with gaps, while the positive dry switching surge strength is basically unchanged.

8. Much work still remains to be done before switching surge values on station insulation can be properly defined and standardized.

9. The insertion of larger diameter units or metallic rain shields into a standard EHV vertical suspension string will materially raise the wet negative switching surge flashover value and the over-all withstand.

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Suppression of Ground-Fault Arcs on Single-Pole-Switched EHV Lines by Shunt Reactors

E. W. Kimbark, *Fellow IEEE*

Summary: Arcing line-to-ground faults isolated by single-pole switching are maintained by capacitive coupling between the faulted and unfaulted phases. Such faults are difficult to extinguish on long EHV (extra-high-voltage) lines because the fault current is proportional to both length and voltage of the line. A promising remedy consists of neutralizing the capacitive coupling by shunt reactors, which are required anyhow on many lines for compensating the normal charging current.

Single-circuit a-c tie lines between power systems ordinarily cannot be regarded as having firm-power capability because 3-pole opening and reclosing cannot be accomplished quickly enough to retain synchronism. Because about 90% of the faults on high-voltage steel-tower transmission lines without overhead ground wires are of the one-line-to-ground type, nearly all of these being transitory, it would seem reasonable to rate the transmission capability of such a tie line by its stability limit for one-line-to-ground faults, *provided that such faults could be successfully cleared and reclosed by single-pole switching.*

Effective single-pole switching would increase the reliability of a line approximately as much as would the addition of overhead ground wires and at a much lower cost.

Arc Extinction with Single-Pole Switching

When one conductor of a 3-phase line is opened at both ends in order to clear a ground fault, this faulted conductor is capacitively and inductively coupled to the two unfaulted conductors, which are still energized at approximately normal circuit voltage and carrying load current. This coupling has two effects:

1. Before extinction of the fault arc, it feeds current to the fault and maintains the arc.
2. After the arc current becomes zero (as it does twice per cycle), the coupling causes a recovery voltage across the arc path. If the rate of rise of recovery voltage is too great, it will reignite the arc.

Of the two types of coupling, the capacitive coupling is the more important. Its importance increases with increase of circuit voltage, and it is the only type of coupling considered in detail in this paper.

The arc on the faulted conductor after it has been switched off is called the secondary arc. Extinction of the secondary arc depends on its current, recovery voltage, length of arc path, wind velocity, and perhaps on other factors. Recovery voltage and length of arc path both increase with circuit voltage and thus the effect of one factor may partially offset the other. This leaves the magnitude of the secondary arc current as the most significant index of whether the arc will be self-extinguishing. For given interphase capacitance, the secondary arc current is proportional to the circuit voltage and to the length of the line section that is switched out. Hence, the length of section on which single-pole switching can be employed successfully is inversely proportional to the circuit voltage. The situation is unfavorable on EHV lines because the circuit breakers are expensive, and it would be desirable to make the sections even longer than is customery at lower voltages. At 500 kv, the estimated permissible length is about 50 miles.

Proposed Method of Arc Suppression

Since coupling of the faulted conductor to the sound conductors through the shunt capacitive reactance between phases is the chief cause of the secondary arc current and recovery voltage, it is proposed to neutralize this capacitive reactance by means of lumped shunt inductive reactance, equal and opposite to the capacitive reactance. The proposed scheme is analogous to the use of a Peterson coil, and both might well be called ground-fault neutralizers. However, the scheme

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now proposed would neutralize the capacitance between phases, amounting to $C_1 - C_0$ per phase; that is, the difference between the positive-sequence and zero-sequence capacitances, whereas the Peterson coil neutralizes the capacitances to ground, $3C_0$. A further difference is that, whereas one Peterson coil can suppress ground faults anywhere on an entire transmission network, the reactors used with single-pole switching must be used on every transmission line too long for secondary arc extinction without them and must be switched with the line. Thus, a large number of reactors might be required.

However, many EHV lines require shunt reactors for wholly or partly compensating the normal, positive-sequence charging current. By proper connection, these reactors can be made to serve the additional purpose of ground-fault suppression at a moderate additional expense.

Connection Schemes and Susceptances of Shunt Reactors

Equivalent Circuits of Shunt Capacitances

To understand the ways in which shunt reactors may be connected, one must first know the equivalent circuits for the shunt capacitances of a 3-phase line. The most general equivalent circuit for the capacitances between four conductors (line conductors a, b, c, and ground) has a branch joining each pair of conductors, Fig. 1(A). The three capacitances of the delta terminating on a, b, and c can always be replaced by an equivalent Y as in Fig. 1(B). These two circuits are valid for both balanced and unbalanced lines, though the labels on the capacitances are valid only for balanced lines. For balanced lines, the 4-branched star circuit of Fig. 1(C)is also correct.

The capacitances of all these circuits are labeled in terms of the zero-sequence capacitive susceptance B_0' or reactance X_0' and the positive-sequence capacitive susceptance B_1' or reactance X_1' of the line. The correctness of the labeled values is most readily checked in Fig. 1(B), as follows: If zero-sequence voltages are applied from a, b, c to ground, charging current flows only in the grounded capacitances, each of which should therefore have susceptance B_0'. If positive-sequence voltages are applied, the grounded Y and the ungrounded Y are effectively in parallel. Hence, the total susceptance per phase must be B_1', and the ungrounded capacitances must make up the difference $B_1' - B_0'$. In Fig. 1(C), with positive-sequence voltage applied, currents are confined to the Y-connected capacitances, which should therefore have reactances X_1'. With zero-sequence current I_0' applied, the zero-sequence voltage is

$$V_0 = jX_0'I_0' = jX_1'I_0' = jX_n'3I_0' \quad (1)$$

whence

$$X_n' = \frac{X_0' - X_1'}{3} \quad (2)$$

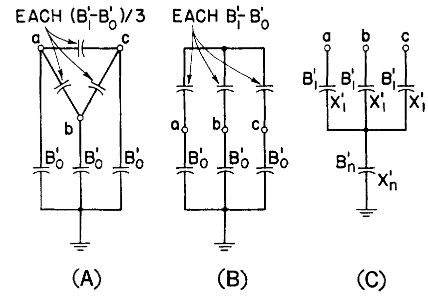
and

$$B_n' = \frac{3B_0'B_1'}{B_1' - B_0'} \quad (3)$$

Connections of Reactors

The shunt-reactor schemes of Figs. 2(A) through 2(C) are analogous to the equivalent-capacitance circuits of Figs. 1(A) through 1(C), respectively. Fig. 2(D) indicates a 3-phase reactor having mutual reactance X_m between phases. Its equivalent circuit in Fig. 2(E) has the same form as the star con-

Fig. 1. Equivalent circuits of the shunt capacitances of a 3-phase transmission line



nection of Fig. 2(C), hence the analysis to be made of the latter is applicable to the former also.

Comparison of Schemes

The aggregate reactive-power rating of the group of shunt reactors is the same in the schemes of Figs. 2(A), 2(B), and 1(D), being that required for shunt compensation under normal conditions. In the 4-reactor scheme of Fig. 2(C), the aggregate rating of the three main reactors has that same value. In addition, there is the fourth or grounded reactor which is energized only during a line-to-ground fault and which, for high degrees of shunt compensation, has a momentary rating equal to only a small per cent of the aggregate rating of the three main reactors.

If the cost of reactors were directly proportional to their ratings, all schemes would cost approximately the same. But, because the cost per kilovar decreases with increasing rating, the scheme having the fewest and biggest reactors costs the least, provided that the reactors are not too big for shipping and handling. The number of high-voltage bushings also significantly affects the cost.

The numbers of reactors and bushings required are as listed, assuming single-phase construction except for Fig. 2(D).

Scheme of Figures	*2(A)*	*2(B)*	*2(C)*	*2(D)*
Number of:				
Reactors	6	6	4	1
High-voltage bushings	9	6	3	3
Medium-voltage bushings	0	3	0	0
Low-voltage bushings	0	0	4	0

On these grounds, the 3-phase reactor of Fig. 2(D) is preferable if it is not too big. If it is, the 4-reactor scheme of Fig. 2(C) is the next choice. In both these schemes, however, the degree of shunt compensation cannot be switched without losing the correct neutralization of interphase capacitance for fault suppression. The 6-reactor scheme of Fig. 2(B) has the advantage that the grounded reactors can be switched on or off or their reactance varied without affecting the neutralization.

The 6-reactor scheme of Fig. 2(A), as compared with that of Fig. 2(B), requires three additional high-voltage bushings and better insulation for the delta-connected reactors, and it has no compensatory advantages. The scheme of Fig. 2(A) will be dismissed, therefore, from further consideration.

Required Susceptances or Reactances

Because the reactors are in parallel with the line capacitances, it is more convenient to express their values in terms of susceptance B than reactance X. Unprimed letters B and

X will be used to denote inductive susceptance and reactance, and the corresponding primed letters B' and X' stand for the respective capacitive quantities.

The requirements are:

1. For fault suppression by neutralization of the interphase capacitances,

$$B_1 - B_0 = \omega(C_1 - C_0) = B_1' - B_0' \qquad (4)$$

2. For shunt compensation of degree F,

$$B_1 = F\omega C_1 = FB_1' \qquad (5)$$

From equations 4 and 5, it follows that

$$B_0 = B_0' - (1-F)B_1' \qquad (6)$$

The required susceptances or reactances of the reactors are found by using equations 4, 5, and 6 in conjunction with the appropriate pair of equations which follow.

The susceptances of the reactors in Fig. 2(B) in terms of zero- and positive-sequence susceptances are

$$B_g = B_0 \qquad (7)$$

$$B_u = B_1 - B_0 \qquad (8)$$

In Fig. 2(C), the susceptances are

$$B_p = B_1 \qquad (9)$$

$$B_n = \frac{3B_0B_1}{B_1 - B_0} \qquad (10)$$

and the corresponding reactances are

$$X_p = X_1 \qquad (11)$$

and

$$X_n = \frac{X_0 - X_1}{3} = \frac{B_1 - B_0}{3B_0B_1} \qquad (12)$$

For the *6-reactor scheme*, Fig. 2(B), equations 8 and 4 yield:

$$B_u = B_1' - B_0' \qquad (13)$$

while 7 and 6 yield

$$B_g = B_0' - (1-F)B_1' = FB_1' - B_u \qquad (14)$$

Equation 13 shows that the ungrounded reactors must resonate with the interphase capacitive susceptance. These reactors provide a degree of shunt compensation

$$F_{\min} = \frac{B_1' - B_0'}{B_1'} = 1 - \frac{B_0'}{B_1'} = 1 - \frac{X_1'}{X_0'} \qquad (15)$$

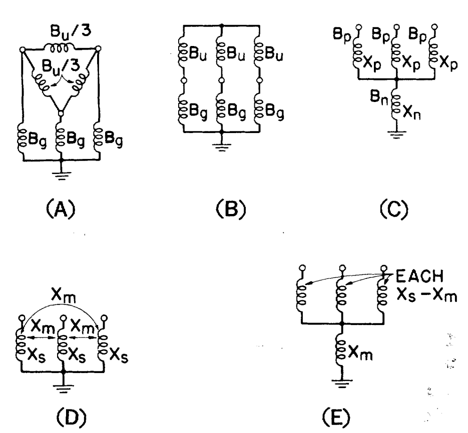


Fig. 2. A, B, C, D — Possible connections of shunt reactors for fault suppression and compensation of charging current. E—Equivalent circuit of D

which, for a typical EHV line without ground wires, is about 30%. If a higher degree F of shunt compensation is desired, it may be obtained by the addition of grounded reactors having the susceptance given by equation 14. For 100% shunt compensation $F=1$), this susceptance is simply $B_{g100} = B_0'$. The grounded reactors play no part in fault suppression.

For the *4-reactor scheme*, Fig. 2(C), equations 9 and 5, yield

$$B_p = FB_1' \qquad (16)$$

while 10, 6, 5, 4 yield:

$$B_n = \frac{3FB_1'[B_0'(1-F)B_1']}{B_1' - B_0'} = B_n'[1-(1-F)B_1'B_0'] \qquad (17)$$

Equation 16 shows that the phase reactors furnish the desired degree F of shunt compensation. The minimum degree, however, is given by equation 15. At this degree B_n, given by equation 17, vanishes, showing that the phase reactors must have ungrounded neutral. At any greater degree, B_n is positive and the neutral reactor is required for fault suppression. Its susceptance depends on F, as shown by equation 17. For $F=1$, it becomes

$$B_{n100} = \frac{3B_0'B_1'}{B_1' - B_0'} = B_n' \qquad (18)$$

The corresponding reactance is

$$X_{n100} = \frac{X_0' - X_1'}{3} = X_n' \qquad (19)$$

How Shunt Reactors Suppress Fault Arcs

The manner in which a Peterson coil suppresses arcing line-to-ground faults on an otherwise-ungrounded network is well known from both the theoretical and practical standpoints. Shunt reactors operate on the same principle when suppressing line-to-ground faults on conductors isolated by single-pole switching from the rest of a well-grounded network. In both cases, parallel resonance between distributed shunt capacitance of one or more lines and lumped shunt inductance is employed.

As previously stated, the addition of the resonant shunt inductance decreases (1) the current in the fault and (2) the voltage across the fault path after the current ceases.

Theoretically, in a lossless parallel LC (inductance-capacitance) circuit, the net current can be made zero by proper tuning. Actually, in either form of resonant ground-fault suppression, the fault current does not become zero because of (1) imperfect tuning, (2) losses, or (3) harmonics. However, the neutralized current is only 10% to 20% of the unneutralized, capacitively fed fault current. The lower value seems probable with single-pole switching.

The parallel LC circuit continues to oscillate after the fault arc is extinguished. In a perfectly tuned, lossless LC circuit, the frequency and amplitude of the free voltage oscillation would exactly match those of the forced oscillation existing before extinction of the arc. Consequently the faulted conductor would remain at ground potential after extinction of the arc, and there would be no recovery voltage across the arc path. Actually, there would be some difference in frequency due to imperfect tuning and some decrease of amplitude caused by losses. Consequently, the amplitude of the power-frequency recovery voltage would slowly increase. Moreover, because a parallel resonant circuit has unity power factor, the instantaneous recovery voltage increases very slowly in the first quarter cycle after arc extinction at a normal current zero, thereby making arc reignition unlikely.

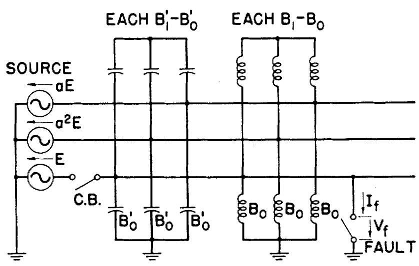


Fig. 3. Equivalent of source and faulted line section, isolated by single-pole switching, series impedance being neglected

By contrast, conditions in the capacitively fed, unneutralized secondary fault arc make extinction more difficult. The fault current and the a-c recovery voltage are in quadrature, so that when the current is broken at a natural zero, the alternating voltage is at its crest value. Consequently, there is a d-c component of voltage due to charge trapped on the isolated conductor. The resultant voltage of the a-c and d-c components is zero at the moment of interruptions, giving a completely offset voltage wave. Half a cycle later, however, the instantaneous recovery voltage reaches twice the crest value of its a-c component. Delayed restriking of the arc is probable.

Because of the low recovery voltage and high power factor of the neutralized fault arc, the current that can extinguish itself is 15 to 30 times higher than in an unneutralized arc.

Arc Current That Can Be Extinguished

In order to estimate the length of line section on which single-pole switching can successfully clear line-to-ground faults, both with and without inductive neutralization, we can utilize (1) the values of arc current that are self-extinguishing on ungrounded systems and systems grounded through Peterson coils and (2) the values of unneutralized arc current on lines having successful single-pole switching.

Peterson Coils

Extensive experience with Peterson coils[1] has shown that the maximum-fault arc currents that are self-extinguishing are:

1. Unneutralized, 5 to 10 amperes.
2. Neutralized, about 150 amperes.

Experience has shown also that faults are successfully cleared with the Peterson coil detuned by 10% or 20%. There is still a resonant circuit which decreases the rate of rise of recovery voltage, even though the frequency of that circuit differs somewhat from the power-system frequency. In a system grounded through a Peterson coil, the detuning arises from switching lines on or off. This cause of detuning will not occur with the scheme herein proposed in which the neutralizing reactors would be switched with the associated line sections. The cited fact shows, however, that, since tuning is not critical, the reactors need not be tunable, and no allowance need be made for differences between capacitances of the three conductors of the untransposed line.

Single-Pole Switching

There are two factors in single-pole switching that differ from Peterson coil operation:

1. The primary arc current is greater than the secondary arc current and may, therefore, establish greater initial ionization.
2. The time in which the secondary arc is extinguished is important so that reclosure rapid enough to give a reasonably high stability limit will be successful.

Information on the unneutralized secondary arc current that permits successful reclosure has been compiled by Maikopar[2] from installations of single-pole switching in many parts of the world. It indicates that with 0.4-second dead time, there is a high probability of successful reclosure if the secondary arc current does not exceed 18 amperes. However, the actual secondary arc current without fault neutralization may be as high as twice the value computed from the voltage and shunt capacitive susceptance. Therefore, we may take the value of 9 amperes of so-computed unneutralized secondary arc current as the maximum permissible value. This value agrees well with the 5 to 10 amperes fault current permissible on an ungrounded system.

As no information has been found on maximum permissible neutralized secondary arc current for single-pole switching, the value obtained from Peterson coil experience (150 amperes) may be used as a rough guide. Even if this be reduced to 75 amperes to give a factor of safety, and if it be assumed that neutralization reduces the secondary arc current to only 20% (instead of 10%) of its unneutralized value, the maximum permissible lengths of section of a typical 500-kv line without ground wires, computed in the Appendixes, are:

1. Unneutralized, 45 miles.
2. Neutralized, 1,800 miles.

The former length is uneconomically short, whereas the latter is much longer than would be used in practice.

Conclusions

It appears from theory and from experience with Peterson coil grounding that the use of shunt reactors for neutralizing the interphase shunt capacitance C_1–C_0 of an EHV transmission line could increase, by a factor of 40 or more, the length of line on which line-to-ground transitory faults could be successfully cleared by single-pole opening and 30-cycle reclosure. Moreover, the same shunt reactors would supply part of the shunt compensation that is usually needed on EHV lines. Thus, fault suppression would be provided at a small additional cost. The scheme merits field tests of its effectiveness.

Successful clearing of transitory line-to-ground faults would greatly improve the reliability of EHV lines without ground

Fig. 4. Simplification of Fig. 3 applicable to first set of emf's

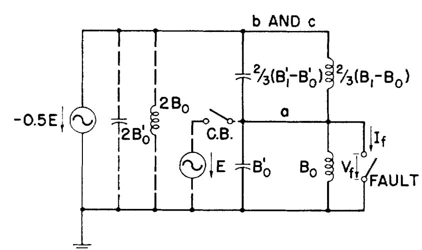
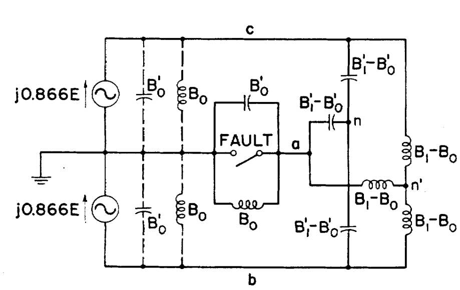


Fig. 5. Simplification of Fig. 3 applicable to 2nd set of emf's



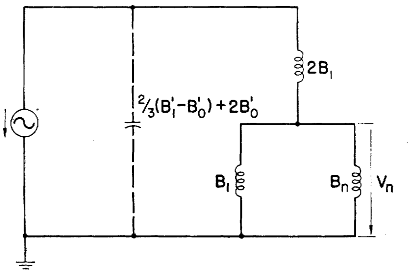


Fig. 6. Equivalent circuit for finding the voltage across the grounded reactor of the 4-reactor scheme during an isolated line-to-ground fault

wires and would make it reasonable to rate the transmission capability of single-circuit a-c ties by their transient stability limits for such faults.

A more detailed analysis of the subject appears in the Appendixes. Appendix I derives equations for the secondary arc current and the recovery voltage of lines with and without neutralization and for the voltage and reactive power ratings of the shunt reactors. Appendix II computes numerical values of these quantities for four typical 500-kv lines.

Appendix I. Circuit Analysis for Single-Pole Switching

Except as noted, longitudinal voltages and impedances are neglected. Consequently, the several shunt elements—the distributed capacitance, the reactors when used, and the line-to-ground fault when present—may be regarded as in parallel; see Fig. 3. The 6-reactor scheme (grounded Y and ungrounded Y) is assumed except when noted to the contrary, and the line capacitance is represented by a like connection. The source is assumed to have balanced, positive-sequence electromotive forces (emf's): $E_a=E$, $E_b=a^2E=-0.500E-j0.866E$, and $E_c=aE-=0.500E+j0.866E$.

The emf's may be resolved into two sets: the real components and the imaginary ones. The first set is $E_a'=E$, $E_b'=E_c'=-E/2$. The second set is $E_a''=0$, $E_c''=-E_b''=j0.866E$. Simplification of the circuit on which the first set acts yields Fig. 4, and simplification of the circuit on which the second set acts yields Fig. 5. From the symmetry of the circuit of Fig. 5 with respect to phase a, it is apparent that phase a is at ground potential. Therefore, there is no voltage across the fault when the fault path is open and no current in it when closed. Thus, the second set of emf's contributes nothing to the fault current or recovery voltage and may be ignored. In computing fault current and voltage, we need consider only the circuit of Fig. 4, disregarding the branches drawn in broken lines, which are directly across the source.

Voltage Across Switch Symbol

The source-frequency recovery voltage across the arc path after the secondary arc is extinguished is the voltage across the switch symbol marked "fault" in Fig. 4 when the switch is open. The voltage $-E/2$ is applied to a voltage divider, each part of which has capacitance and inductance in parallel. The voltage across the lower part of it is

$$V_f=-\frac{E}{2}\cdot\frac{(2/3)[(B_1'-B_0')-(B_1-B_0)]}{(2B_1'/3+B_0'/3)-(2B_1/3+B_0/3)}$$

$$=-\frac{E(B_1'-B_0')-(B_1-B_0)}{(2B_1'+B_0')-(2B_1-B_0)} \tag{20}$$

This voltage vanishes with proper neutralization of $B_1'-B_0'$ by an equal B_1-B_0 supplied by each ungrounded reactor.

The voltage with no neutralization of interphase capacitance is found by putting $B_1-B_0=0$. It is

$$V_f=\frac{E(B_1'-B_0')}{B_0-(2B_1'+B_0')} \tag{21}$$

wherein B_0 is furnished by the grounded reactors. With no shunt compensation whatever, $B_0=0$ also, and

$$V_f=-E\frac{B_1'-B_0'}{2B_1'+B_0'}=-\frac{E1-B_0'/B_1'}{2+B_0'/B_1'} \tag{22}$$

Comparison of equations 21 and 22 shows that shunt compensation by grounded reactors only causes the recovery voltage to be *higher* than it would be with no shunt compensation.

Secondary Arc Current

This is the current through the closed fault switch of Fig. 4, which short-circuits the lower part of the voltage divider. It is

$$I_f=-j\frac{E}{2}\cdot\frac{2}{3}[(B_1'-B_0')-(B_1-B_0)]$$

$$=(-jE/3)[(B_1'-B_0')-(B_1-B_0)] \tag{23}$$

The fault current becomes zero under the same condition under which the fault voltage became zero; namely, by correct neutralization of $B_1'-B_0'$ by B_1-B_0.

Without neutralization, the fault current is

$$I_f=(-jE/3)(B_1'-B_0') \tag{24}$$

It is not affected by grounded shunt reactors.

6-Reactor Scheme

Voltage of the neutral of the ungrounded Y-connected reactors—6-reactor scheme with respect to ground during isolated line-to-ground fault—is dealt with in this section.

During the fault, voltage $-E/2$ of the real set is impressed on the ungrounded reactors, marked (2/3) (B_1-B_0) in Fig. 4. The marked value resulted from a simplification of the connection of two reactors from combined phases b and c to neutral point n'; one reactor thence to phase a, which is grounded by the fault. Thus the voltage from n' to ground is

$$V_n=-\frac{E}{2}\cdot\frac{2}{3}=-\frac{E}{3} \tag{25}$$

where E is the line-to-neutral voltage of the source. V_n is not affected by the imaginary components of source emf. Equation 25 shows that the neutral bushings of the three ungrounded reactors would be momentarily subjected to a third of normal line-to-neutral voltage.

4-Reactor Scheme Isolated Fault

Voltage across the grounded reactor of the 4-reactor scheme during an isolated line-to-ground fault is described by equation 26. The circuit for real components of voltage as in Fig. 4 but with the reactors connected as in Fig. 2(C) simplifies to the circuit of Fig. 6. The voltage across the grounded reactor is

$$V_n=-\frac{E}{2}\cdot\frac{2B_1}{(3B_1+B_n)}=-\frac{EB_1}{3B_1+B_n}$$

$$=-\frac{EX_n}{X_1+3X_n}=-\frac{E(X_0-X_1)}{3X_0} \tag{26}$$

where $X_n=(X_0-X_1)/3$.

4-Reactor Scheme Unisolated

Voltage across the grounded reactor of the 4-reactor scheme during an unisolated line-to-ground fault before the circuit breakers open is calculated herewith.

The calculation consists of two parts. First, the voltage V_n across the grounded reactor is expressed as a fraction of the zero-

Table I. 500-Kv 60-Cycle 3-Phase Lines Used for Illustration

Line number	1	2	3
Number of Conductors per Phase	2	1	2
Name of Conductor	Falcon	Special Expanded	Chukar
Outer Diameter of Conductor, Inches	1.545	2.50	1.602
Separation Between Conductors of Same Phase, Inches	16	—	60
Spacing Between Centers of Adjacent Phases, Feet	37	33.5	40.7

Table II

	Line Number			
	1	2	3	4
Postive-Sequence Shunt Capacitive Susceptance, B_1', Micromhos/Mile	6.65	5.61	7.52	5.61
Zero-Sequence Shunt Capacitive Susceptance, B_0' Micromhos/Mile	4.59	3.92	5.19	4.42
Ratio B_0'/B_1'	0.69	0.70	0.69	0.79
Normal Charging Current, Amperes/Mile	1.92	1.62	2.17	1.62
Normal Charging Reactive Power, Mvar's/Mile	1.66	1.40	1.88	1.40
Current in Secondary Arc, Amperes/Mile Without Neutralization	0.20	0.16	0.22	0.12
Normal-Frequency Recovery Voltage, Kv, Without Neutralization	33	32	33	22
Length of Line, Miles, for which Secondary Arc Would Be Self-Extinguishing:				
Without neutralization, 9 amperes	45	55	40	78
With Neutralization, 75 amperes	1,850	2,250	1,650	3,300
Grounded Reactor of 4-Reactor Scheme				
Voltage V_n Kv for F=1:				
During Isolated Fault	30	29	30	20
During Unisolated Fault, $Z_0/Z_1=$ 1	29	28	29	20
$Z_0/Z_1=$ 2	—	—	—	30
$Z_0/Z_1=$ 3	54	52	54	—
Momentary Rating Q_n, Kvar's/Mile for F=1;				
During Isolated Fault	40	33	45	26
During Unisolated Fault, $Z_0/Z_1=$ 1	38	32	43	25
$Z_0/Z_1=$ 2	—	—	—	58
$Z_0/Z_1=$ 3	130	116	144	—

sequence voltage of the line at the point where the group of reactors is connected. It is

$$\frac{V_n}{V_0}=\frac{3B_n}{B_1+3B_n} \tag{27}$$

Second, the zero-sequence voltage V_0 is expressed as a fraction of the normal line-to-neutral voltage E. Now we must take into account the series impedances which were neglected when the fault was isolated. Use of the well-known equivalent circuit of a line-to-ground fault—series connection of the three sequence networks—gives:

$$\frac{V_0}{E}=\frac{Z_0}{Z_1+Z_2+Z_0}=\frac{Z_0/Z_1}{2+Z_0/Z_1} \tag{28}$$

at the point of fault. Elsewhere V_0 is less. The highest V_0 at the fault is obtained if the fault is distant from a grounding point, in which case Z_0/Z_1 is substantially that of the line itself. The highest V_0 on the shunt reactors occurs if the fault is near the reactors and far from the grounding points excluding the reactors, and this condition is assumed in some of the calculations of V_n in Appendix II, Z_0/Z_1 being taken as 2 or 3. However, as some reactors may be near grounding points, V_n is calculated also for $Z_0/Z_1=1$.

Reactive Power in Grounded Reactor of 4-Reactor Scheme

$$Q_n=\frac{V_n^2}{X_n}=V_n^2B_n \tag{29}$$

Appendix II. Numerical Calculation for Typical 500-Kv Lines

Description of Lines

Computations of normal charging current and reactive power, of secondary fault current and recovery voltage for a line-to-ground fault without neutralization, and of the shunt compensation required for fault neutralization are made for three different designs of 500-kv lines described in Table I.

None of the lines in Table I has ground wires, and the average height of the conductors above ground is assumed to be 50 feet, corresponding to a minimum ground clearance of 35 feet. In order to determine the effect of ground wires, similar computations were made for a variant of line 2:

Line 4 is like line 2 except that two ground wires are added. They are assumed to be 33.5 feet apart and 16.8 feet above the line conductors.

Results of the computations are given in Table II. The ratio B_0'/B_1' is very nearly the same for each of the three basic designs, being about 0.7. The addition of ground wires increases this ratio to approximately 0.8, but ground wires presumably would not be used with single-pole switching.

Nomenclature

$a=\exp(j2\pi/3)=(1+j\sqrt{3})/2$
$B=1/X=$ inductive susceptance of the shunt reactors of a section of line
- $B_0=$ zero-sequence
- $B_1=$ positive sequence
- $B_g=$ inductive susceptance of each grounded reactor of the 6-reactor scheme
- $B_{g100}=$ value of B_g required for $F=1$
- $B_u=$ inductive susceptance of each ungrounded reactor of the 6-reactor scheme
- $B_n=$ inductive susceptance of the grounded reactor of the 4-reactor scheme
- $B_{n100}=$ value of B_n required for $F=1$
- $B_p=$ inductive susceptance of each ungrounded reactor of the 4-reactor scheme

$B'=\omega C=$ distributed capacitive susceptance of a section of line
- $B_0'=$ zero-sequence
- $B_1'=$ positive-sequence
- $B_n'=$ capacitive susceptance of grounded leg of 4-branched star equivalent circuit

$C=$ distributed shunt capacitance of a section of line
- $C_0=$ zero-sequence
- $C_1=$ positive-sequence

$E=$ rms positive-sequence line-to-neutral emf of the source
- E_a, E_b, $E_c=$ line-to-neutral phase emf's
- E_a', E_b', $E_c'=$ real components of E_a, E_b, E_c
- E_a'', E_b'', $E_c''=$ imaginary components

$F=B_1/B_1'=$ degree of shunt compensation, per unit
- $F_{min}=$ at least degree of shunt compensation when reactors are used for fault neutralization.

$I_f=$ rms current of secondary arc, isolated line-to-ground fault
$I_0'=$ zero-sequence charging current of line
$j=\sqrt{-1}$
$Q_n=$ reactive power consumed by neutral (grounded) reactor of the 4-reactor scheme during a line-to-ground fault
$V_f=$ rms source-frequency recovery voltage across path of secondary arc
$V_n=$ rms source-frequency voltage from neutral of reactor group to ground
$V_0=$ zero-sequence voltage of line at shunt reactors or at the fault
$X=\omega L=$ inductive reactance of shunt reactors, with subscripts as for B. In addition,
- $X_s=$ self-reactance per phase of 3-phase reactor
- $X_m=$ mutual reactance between phases of 3-phase reactor

$X'=1/B'=$ shunt capacitive reactance of line, with subscripts as for B'
$Z=$ impedance of system seen from point of fault
- $Z_0=$ zero-sequence
- $Z_1=$ positive-sequence
- $Z_2=$ negative-sequence

$\omega=2\pi f=$ angular frequency, in radians per second

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Note: This last reference was called to the author's attention by a reviewer after submission of the present paper to the IEEE.